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Short communication

Modelling creep behaviour of the human intervertebral disc

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1. Introduction

Mechanical loading on the spine is mainly axial loading, caused by gravity and muscle forces. The diurnal loading pattern in humans typically consists of 16 h loading and 8 h of relative rest (van der Veen et al., 2005; O’Connell et al., 2011b). This loading pattern leads to an overall decrease of disc height during daytime and an increase during the night. In-vitro measurements showed asymmetrical mechanical behaviour of the disc with respect to loading and unloading. A long recovery time was required to compensate the effect of the loading phase (van der Veen et al., 2005, 2007).

The deformation of the intervertebral disc is non-linear and time dependent. It is typically a decay function in which two regimes are superimposed. During the first regime the deformation rate is high, during the second regime the deformation rate progressively slows down (Johannessen et al., 2004; van der Veen et al., 2005). The time constant of the long-term behaviour is the time constant of the second regime. In recent literature, various models have been used to describe and predict deformation of the disc over time: e.g., a stretched exponential function model (KWW) (Johannessen et al., 2004) and a Double-Voight model (DV) (O’Connell et al., 2011a). The time constant of the slow regime varies from minutes in small animals to hours in humans (O’Connell et al., 2011a; Boxberger et al., 2009).

The time constant for loading in human discs was estimated at 4 h (O’Connell et al., 2011a). However, the test duration in these experiments (4 h) was too short in comparison to the diurnal loading time. The overall loss of disc height was calculated by extrapolating the measured change in disc height in time. However, the validity of these extrapolations can be questioned.

In this study, we investigated the choice of model and the effect of testing time on the validity of predictions on creep behaviour of human discs. We hypothesised that the choice of model and test duration influences the prediction. To this end, we determined creep behaviour in human intervertebral discs with test durations beyond the typical duration of in vivo loading.

2. Material and methods

Ten intervertebral discs (IVDs; T9-T10; T10-T11 and T11-T12) were obtained from five human spines. The spines varied in age from 54 to 84 years. Spinal segments (i.e., the intervertebral disc and half of both the adjacent vertebral bodies) were cut from the spines with a band saw by two parallel cuts. All posterior elements were removed. Motion segments with osteophytes, vertebral fractures and/or disc narrowing were excluded from the experiment. The frozen discs were thawed immediately before testing. Tests were performed at room temperature. To prevent dehydration tests were performed in a saline bath. Since the overall testing time was 60 h an antibiotic (penicillin (200 mg/ml) and streptomycin (250 mg/ml)) was added.

The loading protocol was based upon in vivo intradiscal pressure measurements in humans by Wilke et al. (1999). The nucleus pressures in humane discs...
Varies between 0.1 MPa for lying in prone position to more than 2.0 MPa during lifting activities. The test load represented lying in prone position during preload and unloading phases (0.1 MPa) and standing upright during the loading phase (0.8 MPa). The duration of the test was based upon the time constants as reported in literature (O’Connell et al., 2011a). The complete test cycle consisted of three phases. IVDs were first preloaded for 12 h. The preload was then followed by a loading phase of 24 h and an unloading phase of 24 h. The duration of the loading phase was equal to six times the reported time constant.

Loads were applied by an Instron hydraulic testing devise (Instron 8872 Canton, Massachussetts). Prior to the test, the transverse area of each vertebra was measured. This area was used to calculate the appropriate compressive load. The load was applied to the superior vertebral body of the spinal segment and built up in 30 s. The compression load on and vertical displacement of the superior vertebral body was measured during testing with a sample rate of 10 samples per second.

Two different methods to calculate the parameters of the creep phase were used (i.e. deformation under constant load). Both methods are commonly used in literature, a Kohlrausch Williams Watts function (KWW; Eq.(1)) and a Double-Voight model (DV; Eq.(2)).

\[ \varepsilon(t) = d_0 (1 - e^{-t/\tau_f}) \]  
\[ \varepsilon(t) = \left( \frac{1}{S_1} (1 - e^{-t/t_1}) + \frac{1}{S_2} (1 - e^{-t/t_2}) \right) \]  

The KWW function is a stretched exponential function. The three parameters of this model are: the change of disc height at equilibrium \( (d) \) thus when the elapsed time equals infinity; the time constant \( (\tau_f) \) and the stretch parameter \( (\beta) \). A stretched exponential function describes a decay function with two regimes. For a stretched exponential function with beta in the interval 0 < \( \beta \leq 1 \), it describes an initial response described by a faster-than-exponential-decay regime followed by a slower-than-exponential decay regime (Berberan-Santos et al., 2005).

A Double-Voight (DV) model represents the mechanical behaviour of two damper/spring models connected in series. The four model parameters are: deformation of the fast Voight model at infinity \( L_{s_f} \), the time constant of the fast Voight model \( \tau_f \), deformation of the slow Voight model at infinity \( L_{s_f} \), and the time constant of the slow Voight model \( \tau_f \). Since creep is defined as deformation under constant load, the parameters are calculated from the time point when the applied load is constant. Thus, the factor \( L_{s_f} \), which describes the deformation prior to the creep phase, was not used.

Model parameters were separately calculated over the loading and the unloading test phase. The models were fitted to the measured data by a least squares method in Matlab (Mathworks Natick MA USA, version 7.1). To determine the effect of test duration, the KWW and DV parameters were calculated from a limited data set which consisted of the first 4, 8, 12, 16, 20 h of the test and finally from the full 24 h.

Since time constants defined in the two models cannot be compared directly, we calculated as model predictions the deformation at equilibrium and a common time constant \( (\tau_{eq}) \) defined as the time it takes to reach 63% of the deformation at equilibrium.

Finally, repeated measures analyses of variance were performed with the duration of the experiment and the choice of model as independent variables and change-of-height at equilibrium and the time-constant as the dependent variables.

3. Results

The change of disc height did not reach a plateau in 24 h of loading or unloading. The length of the unloading phase was insufficient to compensate the loss of disc height during loading (Fig. 1). Moreover, recovery of disc height was still far removed from equilibrium, therefore deformation could not be modelled with sufficient certainty. Therefore, subsequent analyses were restricted to the loading phase.

Both models described the 24 h data of loss of disc height under constant loading well (Fig. 2a). The models provide a nearly insuficient certainty to compensate the loss of disc height during loading (Fig. 1). Moreover, recovery of disc height was still far removed from equilibrium, therefore deformation could not be modelled with sufficient certainty. Therefore, subsequent analyses were restricted to the loading phase.

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Consequently, the model predictions given with the KWW-model and DV-model vary with test durations (Tests of Within-Subjects Effects): Type of model: \( F = 14.47, p < 0.004 \) (Greenhouse-Geisser), Time: \( F = 12.20, p < 0.002 \) (Greenhouse-Geisser) and Type * time: \( F = 15.13, p < 0.001 \) (Greenhouse-Geisser). Predictions differ clearly between models, but seem to converge to the same value with increasing test duration.

Model predictions as a function of test duration are presented in Figs. 3 and 4. As can be seen these predictions are dependent on test duration with effects levelling off at longer experiments. Consequently, the model predictions given with the KWW-model and DV-model vary with test durations (Tests of Within-Subjects Effects): Type of model: \( F = 14.47, p < 0.004 \) (Greenhouse-Geisser), Time: \( F = 12.20, p < 0.002 \) (Greenhouse-Geisser) and Type * time: \( F = 15.13, p < 0.001 \) (Greenhouse-Geisser). Predictions differ clearly between models, but seem to converge to the same value with increasing test duration.

**Table 1**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>KWW</th>
<th>DV</th>
</tr>
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<tbody>
<tr>
<td>( r_f )</td>
<td>17.34 (± 9.29)</td>
<td>12.48 (± 2.47)</td>
</tr>
<tr>
<td>( d_{eq} )</td>
<td>-3.15 (± 0.70)</td>
<td>-2.07 (± 0.55)</td>
</tr>
<tr>
<td>( \beta )</td>
<td>0.67 (± 0.05)</td>
<td>0.82 (± 0.32)</td>
</tr>
<tr>
<td>( d_{eq} )</td>
<td>0.50 (± 0.35)</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 1.** The average changes of the disc height during a constant compression load (0.8 MPa) and subsequent unloading (0.1 MPa).

**Fig. 2.** Typical example of the change of disc height during constant loading. (a) Actual data of one specimen during 24 h of loading and the fit of both models to these data. R-squared of the fit: DV: \( r^2 = 0.9999 \); KWW: \( r^2 = 0.9999 \). (b) The same data with the model fit based on the first four hours of the test, extrapolated to 24 h. R-squared of the fit: DV: \( r^2 = 0.9469 \); 4 h KWW: \( r^2 = 0.9985 \).
Variation in test duration had a larger impact on the KWW model than on the DV model (Figs. 3 and 4). However, both models converge to the true value with increasing test duration. Both models were applied to the creep phase only and not to the first part of the experiment in which the compression load was applied, allowing a direct comparison between both models. The KWW model only describes the creep phase, whereas the DV model in principle also models the immediate response.

The test environment was designed to mimic the in vivo environment of the intervertebral discs as much as possible. The specimens were tested in a saline bath at room temperature to slow down the natural decay and secondly antibiotics were added to the bath to control bacterial growth. Previous experiments in our lab showed that we could test caprine discs in this system for 72 h without a change in mechanical behaviour (van der Veen et al., 2009). This indicates that that decomposition of the disc presumably did not play a role in the outcome of this study. The samples had been frozen prior to the test and were thawed before the experiment. However, freezing and thawing of samples does not influence the biomechanical behaviour of the spine (Dhillon et al., 2001).

In conclusion, we showed that creep of the IVD in compression takes more than 12 h to reach 63% of equilibrium deformation. Although both KWW and DV models describe, experimental data well, typical test durations are too short to obtain valid model parameters. Extrapolation beyond the test duration, even if this exceeds the physiological loading time, yields overestimation of deformation by KWW models and underestimation by DV models.

Conflicts of interest statement

No funds were received in support of this work. No benefits in any form have been or will be received from a commercial party related directly or indirectly to the subject of this manuscript.

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